

Eddies and Thermohaline Intrusions of the Shelf/Slope Front off the Northeast Spanish Coast

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A low-salinity anticyclonic eddy was found during a field study of the shelf/slope front off the northeast Spanish coast in July 1983. The eddy was associated with a tongue of low-salinity, cold water that originated in the Gulf of Lions. Hydrographic stations indicated the presence of multiple salinity-inversion layers. In particular, a relative salinity maximum layer was found at the base of the eddy, which can be traced through the study area along the same isopycnal surface. This suggests the thermohaline intrusion of near-surface, warm, high-salinity, open-ocean water along the frontal boundary. The anticyclonic eddy also induced a strong upwelling and, consequently, a high biological production at the coast. Subduction along the coastal front seems to provide major transport of particulate material into the open sea.

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INTRODUCTION

Off the northeast Spanish coast, density fronts generally exist between shelf and open ocean. The shelf water has lower salinity (salinity < 37.5) than the offshore water (salinity > 38.0) due to river runoff. The most important freshwater inputs in this region are the Rhone River in the northern Gulf of Lions and the Ebro River in the south. In winter the ocean is fairly homogeneous; the shelf water is cooler than the offshore water. In summer there is a pronounced thermocline, but the horizontal temperature difference between shelf and offshore waters is slight, the shelf water being cooler. The shelf/slope front which normally lies directly over the continental slope is essentially a salinity front of moderate horizontal density gradient [Font *et al.*, 1988].

Examination of historical satellite thermal images indicates that ribbons or plumes of cold water are normally seen embedded in the slope region north of the Ebro River [La Violette *et al.*, this issue]. The imagery indicates that these cold water features originated from the Gulf of Lions (Figure 1). In addition, the imagery often shows that these features extruded offshore near submarine canyons as energetic frontal filaments [Maso, 1989]. Filaments also had been documented from in situ measurements at the Balearic Sea [Wang *et al.*, 1988]. A narrow filament about 10 km wide was found moving across the shelf at a speed of about 20 cm/s. The filament was characterized by strong horizontal and vertical velocity shears and strong convergence at its leading edge (the nose).

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On the shelf during summer there are frequently strong, intermittent salinity inversions. Wang *et al.* [1988] suggested that the salinity inversions were associated with the subduction of slope water at the nose of the filament. However, because of limited hydrographic data coverage in that study, they were not able to actually trace the inversion layer. In this paper we reexamine a historical data set of extensive conductivity, temperature, and depth (CTD) stations taken in July 1983 off Barcelona for evidence of the salinity inversions. The effect of subduction on material exchange between shelf and open ocean is discussed.

OBSERVATIONS

The field study was carried out between June 30 and July 4, 1983, aboard the R/V *Garcia del Cid*. The cruise consisted of a survey of the shelf/slope region off Barcelona (Figure 2) with closely spaced (about 10 km) stations. Surface temperature and salinity were continuously monitored using a Grundy MK1 thermosalinograph. Hydrographic stations were obtained using a Neil Brown CTD. In addition, as part of a multidisciplinary study, chlorophyll *a*, nitrates, phosphate, silicate, and biological samples were analyzed at several fixed depths [Grup PEPS, 1986]. Ship positions were obtained by an on-board satellite navigation system. Cloud-free satellite NOAA advanced very high resolution radiometer (AVHRR) infrared (channel 4) imagery for the period of June 28 through July 2, 1983, were examined to infer the regional flow. These imagery have been enhanced and registered into Mercator projections (see La Violette [1987] for the general details of the rationale of using the imagery in this fashion and the methodology used in the image processing).

Examination of the satellite thermal imagery indicates that a portion of an alongshore cold plume was moving through

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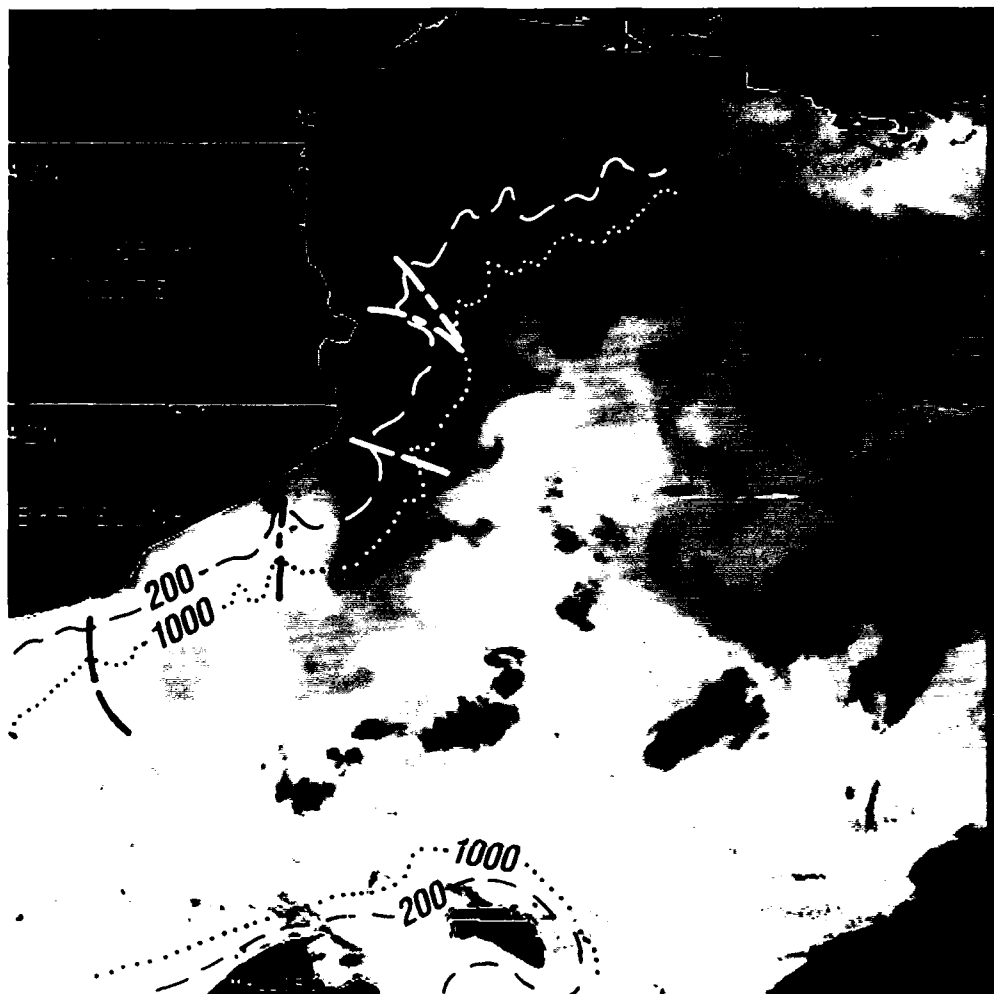


Fig. 1. NOAA AVHRR thermal imagery for September 10, 1986. The northern extension of the cold-water plume indicates its probable origin in the Gulf of Lions. In this and other imagery presented in this study, the darker areas of the imagery are the colder radiated temperatures of the scene (black areas are clouds); the lighter areas are the warmer temperatures. The 200- and 1000-m contours are presented to show the continental and island slope regions [from *La Violette et al.*, this issue].

the study area at a speed of 25 cm/s (Figure 3). The leading edge of this band of cold water was a well-defined anticyclonic eddy over the shelf. In the open ocean and behind the anticyclonic eddy, there is also evidence for cyclonic eddies. Because of contamination by atmospheric moisture, the July 2 image is comparatively indistinct, being only clear enough to indicate that the feature had continued its south-westward translation.

Analysis of individual CTD profiles shows complex vertical structures of temperature and salinity. For example, at station 28 (see Figure 2a for station locations) there were two salinity inversions (relative salinity maximum), or interleaving layers, one at about 25 m and the other at 50 m (Figure 4a). In both layers, temperatures were anomalously warm, which compensates the salinity inversion. A neighboring station (station 21) also indicated two salinity inversions (Figure 4b) but of smaller extent. We also noted that the salinity inversion layers in both stations were located at about the same density surface. The upper inversion layer

centered around 27.0 density surface, and the lower inversion layer at 27.6. This suggests that the salinity inversion may be caused by the thermohaline intrusion along isopycnal surface.

Because of complex vertical structures, it is difficult to contour salinity or temperature at constant depths. Nevertheless, it is still useful to generate slightly smoothed property maps for large-scale water mass distribution. Figures 5a and 5b show temperature and salinity distributions at 10 m (below the immediate surface heating), and Figures 5c and 5d show distributions at 40 m. The temperature structure indicates a pool of cold water in the center of the study area, surrounded by warm water on the southwest and near the coast. Although warm water did not appear in the southeast, there must have existed a thermal front further offshore separating the warm open-ocean water from the cold pool. In other words, the cold pool appears to be a trapped feature connecting to the cold water intruding from the northeast (Gulf of Lions). We also noted that the cold pool in the

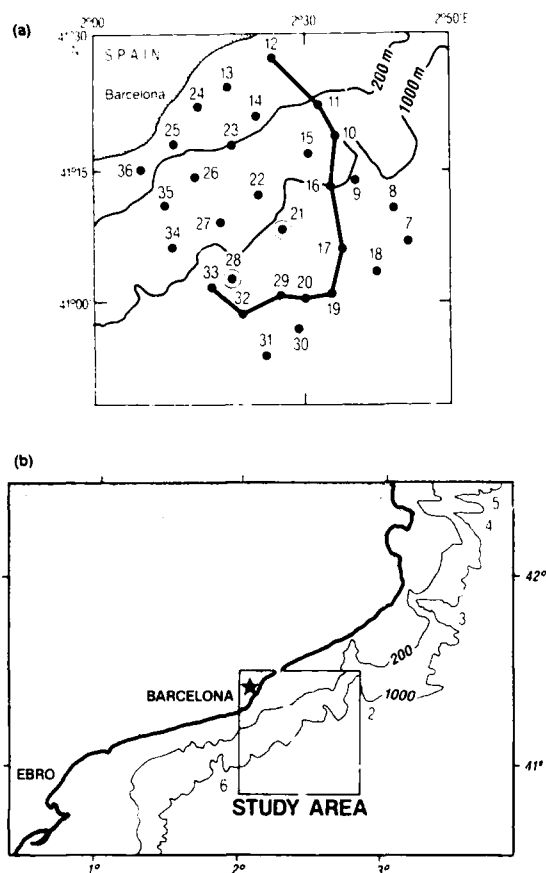


Fig. 2. (a) The station locations and (b) regional topographic features of the study area in the Balearic Sea.

center of the study area was an isolated patch surrounded by warm water. This suggests that a ribbon of warm water was pulled off from the coast and turned anticyclonically in the study area. Similar features often appear in satellite imagery, for example, on the clear image of June 28 (Figure 3). Below the thermocline, because of weak seasonal heating, the horizontal temperature distribution should be homogeneous. However, the shelf water was warmer than the subsurface open-ocean water (Figure 5c). This indicates that the shelf water was not formed locally. The intruded water was cooler at the surface but warmer below 20 m than the open-ocean water.

The surface salinity structure indicated a distinct salinity front on the slope, a plume of low-salinity water on the shelf, and a weak salinity front near the coast (Figure 5b). The shelf/slope front is the major density front that defines the boundary of the shelf water. The salinity structure at 40 m also shows the low-salinity eddy (Figure 5d). There is clear evidence for anticyclonic motion in the eddy, as a tongue of high-salinity water appears to be pulled off from the coast. This high-salinity tongue in fact was located right under the near-surface warm ribbon (Figure 5a). In other words, the low-salinity eddy on the shelf has an anticyclonic sense of rotation. Geostrophic calculation relative to 200-m level indicates that the speed of anticyclonic motion is about 20 cm/s. The low-salinity eddy seems to open to the southwest,

which is consistent with the satellite image that by July 1 there was still a band of cold water intruding southwestward.

At the perimeter of the eddy there were two sharp frontal features: a shelf/slope front at the offshore boundary and a coastal front at the nearshore boundary. Figure 6a shows a vertical transect of salinity on the density coordinate, and Figure 6b shows the corresponding isopycnal depths. The transect consists of two segments, stations 12 to 19 across the eddy and stations 19 to 33 across the shelf/slope front (Figures 2a and 4). On a constant density surface, the eddy water type was cooler and fresher than the ambient water. In addition, there was a clearly defined relative salinity maximum layer (marked by dashed line in Figure 6a). This salinity maximum layer, which corresponds to the second inversion layer displayed in the two CTD profiles (the inversion layer at 50 m in Figure 4a, and at 55 m in Figure 4b), can be traced through the entire area. Also, despite large variations of the isopycnal depth (Figure 6b), the salinity maximum layer lies essentially on the same density surface. This remarkable consistency is clear evidence of the thermohaline intrusion, that is, the subduction of warmer and higher-salinity open-ocean water along an isopycnal surface.

Thermohaline intrusion can occur on any density surface. However, the intrusive layer appears to concentrate on the 27.6 density surface, which is the base (on the density coordinate) of the eddy (Figure 6a). This suggests that the subduction of open-ocean water is along the edge of the intruding eddy. Also, the 27.6 density surface intercepts the open ocean (Figure 7) at about 25-m depth, the base of the thermocline. This may not be coincidental because above the thermocline the intrusive water will be quickly mixed by wind stirring. Nevertheless, we did observe a major intrusive layer at station 28 above the 27.6 density surface (Figure 4a). The observed salinity of 38.10 and temperature of 20.05°C was the highest observed salinity and temperature value at that depth (25 m) for all stations. The source water must have originated from the surface water farther offshore. This intrusive layer probably was formed during the light wind condition (wind was <5 m/s in the sampling period from stations 23 to 28), but it disappeared 6 hours later at station 32 during a period of gusty wind (wind >10 m/s after station 31).

There was also a sharp salinity front near the coast (Figure 5b), particularly in the subsurface (Figure 5d). The water type of the coastal front is the same as that of the shelf/slope front (Figure 6a), suggesting that prior to the intrusion of the cold, low-salinity plume the study area was occupied by open-ocean water. When the anticyclonic eddy moves against the coast, it probably pulls surface water away from the coast, causing flow divergence or upwelling. The coastal front appears to be generated mainly by this nearshore upwelling, since only below 40 m the density front is fully developed (Figure 6b). The upwelling hypothesis also is supported by the presence of exceedingly high chlorophyll *a* and plankton concentrations at the coastal front [Estrada and Salat, 1989; Flos and Tintoré, 1990]. We noted that the nutrient supply from coastal runoff may also contribute to the plankton bloom.

CONCLUSION

Our observations have documented a low-salinity anticyclonic eddy on the northeast Spanish shelf off Barcelona.

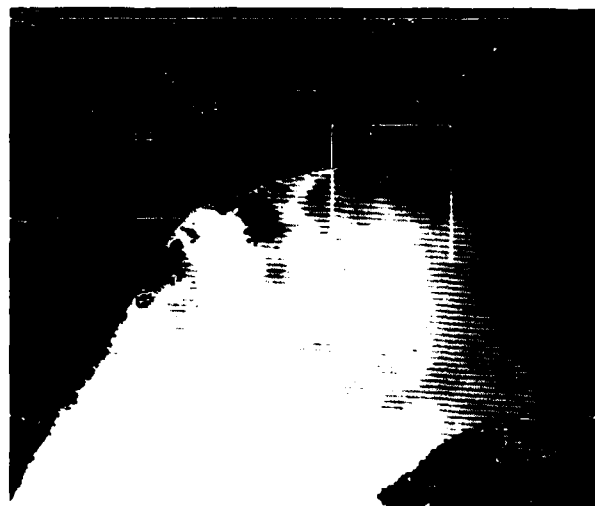
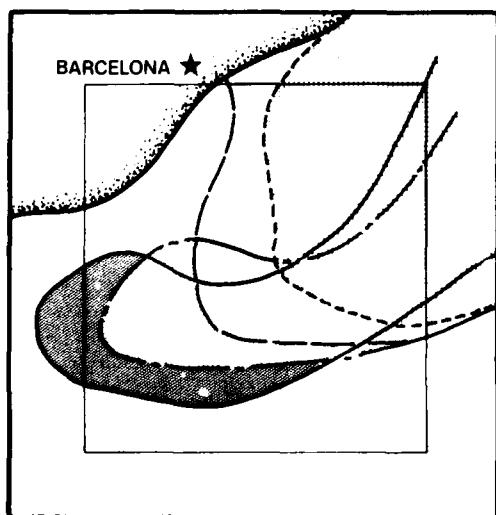
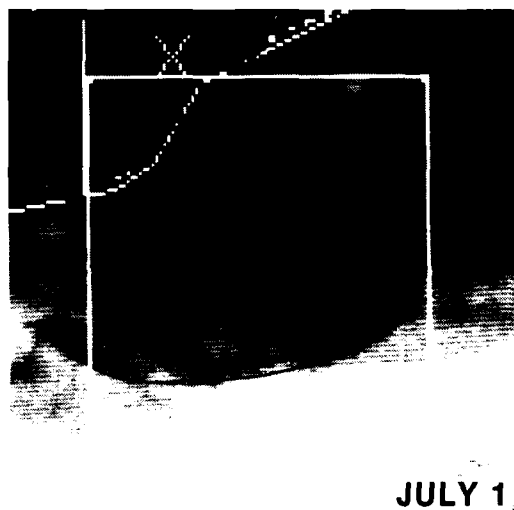
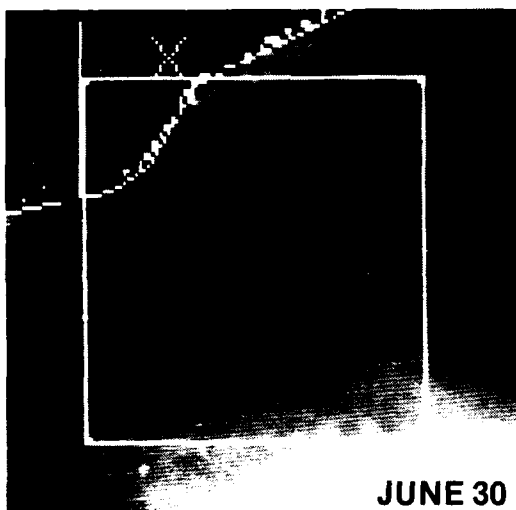
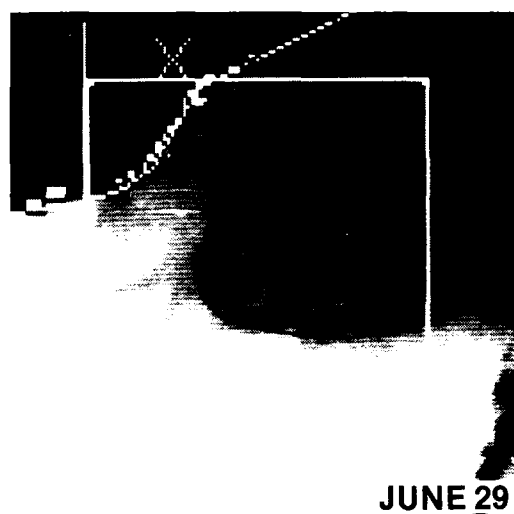
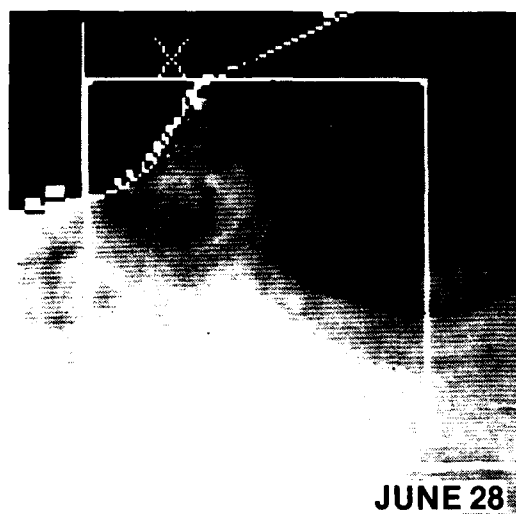


Fig. 3. The southward advection of the leading edge of the cold-water plume as detected in the NOAA AVHRR satellite imagery for 4 days. Measurements of the displacement from image to image indicated a transition rate of 25 cm/s. The bottom right image shows the entire Balearic Sea to provide a broader perspective of the feature.

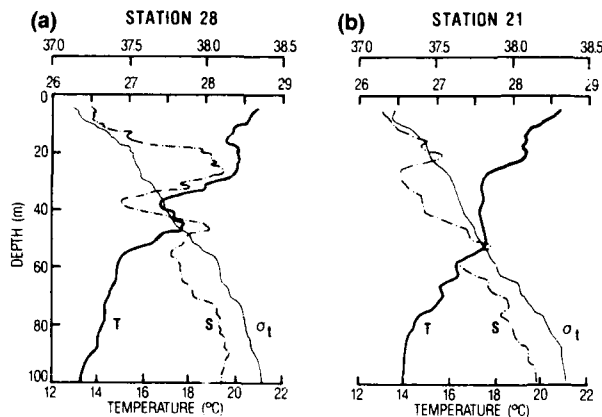


Fig. 4. Individual CTD profiles for stations 21 and 28 (see Figure 2 for locations).

The eddy appears to be the southward extension of the coastal flow from the Gulf of Lions. The anticyclonic motion in the eddy may be generated by the vorticity adjustment within the buoyant gravity current. As the buoyant plume moves southward, the density interface becomes shallower, and the plume will acquire anticyclonic vorticity. This process is clearly illustrated in a numerical model study of

buoyant flow from estuaries and straits [Wang, 1987]. Houghton *et al.* [1986] also found a tongue of shelf water turning anticyclonically near the shelf break in the Mid-Atlantic Bight. The anticyclonic motion may also be generated by topographic interaction. Historical hydrographic data and satellite remote sensing suggest that the region off the northeast Spanish coast is a "permanent" boundary between the cool northern water and the warm Balearic Sea shelf water. As this region is located just downstream of the last of a series of prominent canyon systems (Figure 2b), the anticyclonic eddy could also be generated through the interaction between the southward coastal flow and the canyon. When currents move over the canyon, the total water column is stretched, and a cyclonic eddy is generated. Downstream of the canyon, an anticyclonic eddy also will be generated, so that the net vorticity is conserved. The anticyclonic eddy may remain trapped near the canyon if the vorticity-vorticity interaction is dominant [Huppert and Bryan, 1976]. The topographic interaction is suggested by the satellite image in June 28 (Figure 3), which shows a pair of counterrotating eddies with the cyclonic one over the canyon.

It is interesting to compare this study with the 1986 observation made on the Balearic Sea shelf (about 100 km southwest of Barcelona). In June 1986 a narrow (about 10 km wide), rapidly evolving filament was found in the slope

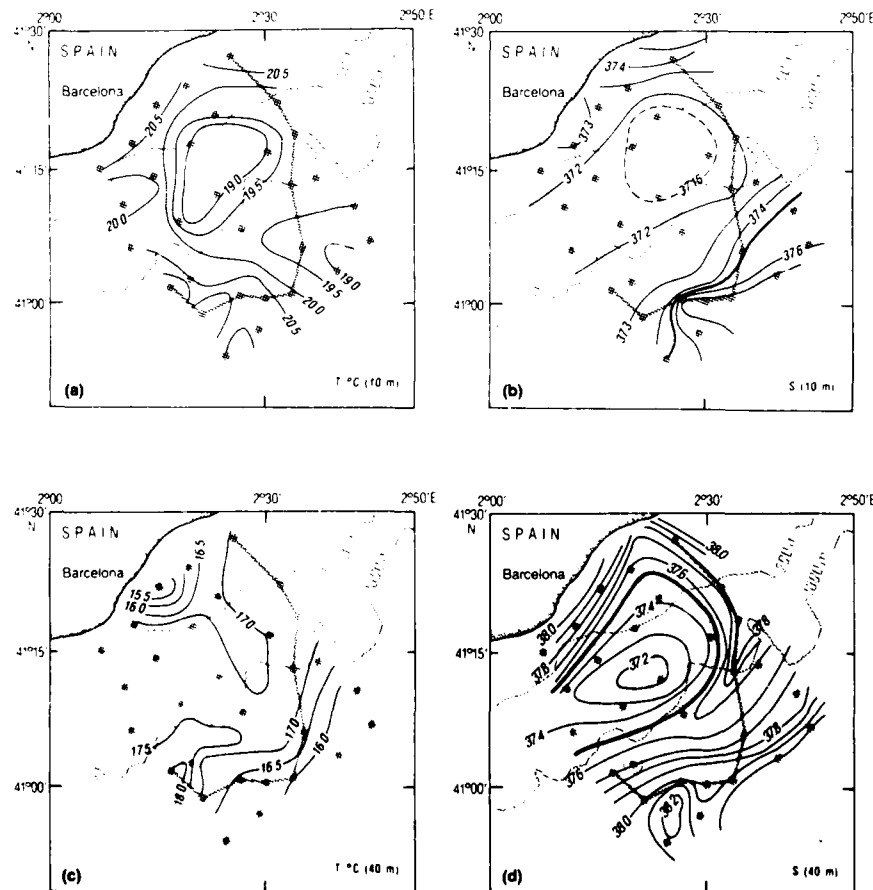


Fig. 5. Temperature and salinity distributions for 10 m and 40 m.

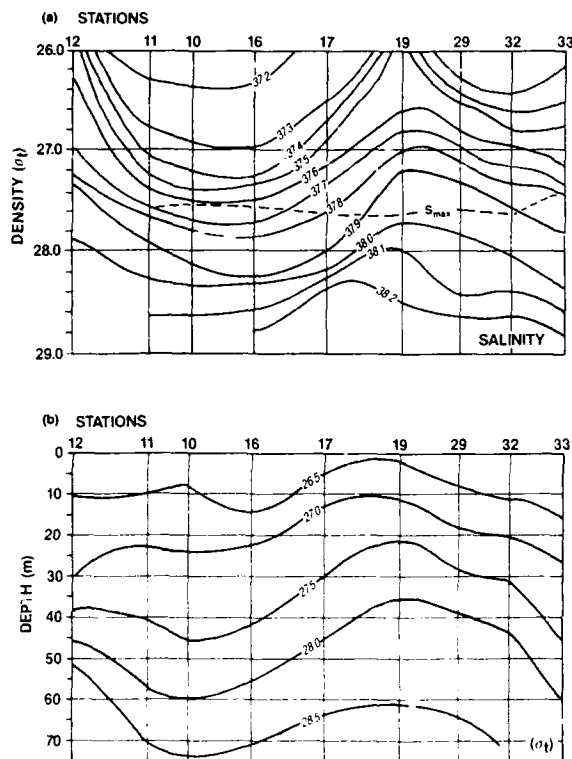


Fig. 6. (a) A salinity transect along line A (see Figure 2). The vertical coordinate is density. (b) The same transect showing the vertical distribution of the density surface.

region whose displacement induced strong convergence [Wang *et al.*, 1988]. The filament existed only in the upper layer, and salinity inversions were found at the thermocline, which is the base of the filament. In this study the eddy had a diameter of about 50 km, and salinity inversions were found at the base of the eddy (the 27.6 density surface). Thus, while the scale and the energetic are different, filaments and eddies both contribute to vigorous exchange of water mass across the shelf/slope front through subduction

(thermo-haline intrusion). Flament *et al.* [1985] also found subduction along an upwelling filament off northern California.

The subduction process not only is effective in the water mass exchange, it also appears to have major impact on the transport of particulate matter. Estrada and Salat [1989] found a well-marked deep chlorophyll maximum (DCM) layer in the shelf and the open sea (extending over 100 km offshore) during this same study. The DCM layer was at about 70-m depth, which is the base of the low-salinity eddy. This suggests that the high concentration of chlorophyll in the coastal zone is subducted along the coastal front and eventually spreads into the open sea. Estrada and Salat also found that the plankton species in the DCM layer in the open sea is closely related to the coastal species. Thus the eddy exchange process may also lead to significant export of particulate material from the coastal zone into the open sea [Flos and Tintoré, 1990].

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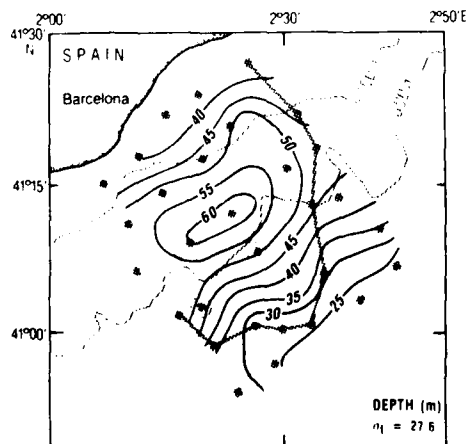


Fig. 7. The depth of the 27.6 density surface.

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